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ACCRETION IN MIXED CLOUDS

by

W. C. Macklin

Imperial College, London

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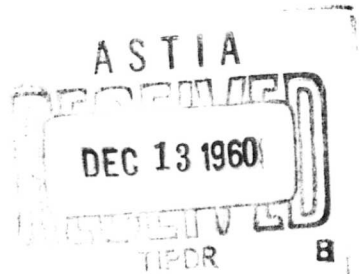
W.C. Macklin
Imperial College, London

CONTENTS

Abstract

It has been found experimentally that the rate of accretion of ice and the nature and structure of the ice deposited on a body moving in a supercooled cloud is affected by the presence of ice particles in the cloud; there are important implications to the growth of hailstones.

1. Introduction

In his treatment of the growth of hailstones, Ludlam (1958) distinguishes between the "dry" and "wet" growth regimes. If an ice particle is growing in a supercooled cloud by the accretion of water droplets then the temperature of its surface is higher than that of its surroundings due to the release of the heat of fusion (Schumann 1938, Ludlam 1950). If the rate of accretion increases because of either an increase of the liquid water concentration of the cloud or an increase in the size and therefore fallspeed of the particle, then the temperature of the accreting surface is raised still farther until the transfer of heat to the environment by conduction and evaporation again just balances the rate of liberation of heat by the freezing droplets. There is, however, an upper limit to the surface temperature, namely $0^{\circ}C$, the melting point of ice. For given values of the ambient temperature, fallspeed and diameter of the accreting particle, there is a critical liquid water concentration, W_c, which will just maintain the surface temperature at $0^{\circ}C$. When the concentration of cloud water is less than W_c, the surface temperature is below $0^{\circ}C$, all the accreted water is frozen, and Ludlam speaks of growth in the "dry" regime. On the other hand, when the concentration exceeds W_c, more water is collected than can be frozen; the rate of growth of the ice mass is determined solely by the heat transfer into the environment and Ludlam refers to growth in the "wet" regime. It must be pointed out, however, that there is no sharp transition in the state of the particle surface; the fraction covered by freezing droplets at any instant increases continuously as the surface temperature approaches $0^{\circ}C$. Ludlam assumed that when the cloud water concentration is greater than W_c, the excess collected by the

ice particle accumulates as a liquid film, beneath which a layer of ice of density about 0.9 g cm^{-3} is deposited, or is shed into the wake of the particle.   Since entry into the wet growth occurs with rather small cloud water concentrations when the ice particle has the size of a hailstone, it has been regarded as greatly restricting the growth rate of natural hailstones;   for example, the rate of increase of radius of a hailstone 1 cm in diameter growing "wet" at $-10^{\circ}C$ in a supercooled cloud having a water concentration of 6 g m^{-3} (about the maximum to be anticipated inside large cumulonimbus) is about $1/4$ of the value it would be if all the accreted water could be frozen.   At higher liquid water concentrations and cloud temperatures and for larger stones, this fraction is even smaller.

In an experimental investigation of the factors affecting the density of ice formed by accretion (to be published elsewhere) the writer found that when the cloud liquid water concentration exceeded the critical value, the excess water which could not be frozen was not shed into the wake of the accreting object, as had been assumed, but was incorporated into the ice structure, producing a "spongy" or "mushy" deposit containing a substantial fraction of unfrozen liquid.

This phenomenon is well-known to operators of icing tunnels.   Fraser, Rush and Baxter (1952) describe experiments which resulted in deposits from which water could be squeezed "as though from a wet sponge".   List (1959) has obtained deposits containing up to 72% of liquid water.   This type of ice has also been observed, under certain conditions, on aircraft flying through supercooled clouds (see, e.g., Brun, 1957).

It was further noticed during the experiments that ice crystals occasionally present in the airstream became incorporated into rime

structures and could be seen glinting in the surface.   The number of ice crystals swept up in this way depended on the condition of the surface, and when the surface was wet, appreciable quantities of small ice particles, deliberately introduced into the airstream, were collected. This has been observed by other investigators working on problems of ice accretion.   Clark (1948) describes experiments carried out at the Mount Washington Observatory, U.S.A., in which objects were exposed in the supercooled cloud at the summit.   Snow and fragments of rime were sometimes seen embedded in the accreted ice.   Minervin (1956) states that when measurements of liquid water concentration are made by accretion instruments in supercooled cloud, the measured values of the liquid water concentration may exceed the critical value for the instrument because ice crystals become frozen into the newly formed ice.

It is apparent that these two phenomena, the formation of mushy or spongy ice and the accretion of ice particles as well as supercooled droplets could well affect the growth of hail in the wet condition. Gaviola and Fuertes (1947) assert that the "use of snow as a building material (of hailstones) in addition to sub-cooled water droplets, makes the growth to large sizes ...... easier and explains the concentric layers".   Landis (1907) describes large oblate hailstones (about $2\frac{1}{4}$" by $1\frac{3}{4}$") having layers which were "undoubtedly moist snow".   Pollard (1936) has also described hailstones with layers which appeared to be "snow frozen hard".   These last two interpretations cannot be accepted without reserve, however, as there are varieties of rime ice which could give such impressions.

New interest has been aroused by the observation (Ludlam 1959) that only "glaciated" cloud towers, presumably containing a considerable proportion of frozen particles, have been found with rising speeds of the magnitude believed necessary for the production of large hailstones. Moreover, field data seemed also to indicate that the growth-times previously computed for large stones were excessive and, therefore, that the restriction by the entry into the wet growth regime was not so severe as had been assumed. The writer therefore undertook the experiments on ice accretion in mixed clouds which are described below.

2. Experimental procedure

A small wind tunnel with a working section 20 cm square, and capable of producing wind speeds of 13 to 14 m/s, was installed in a cold room. This room was roughly a cube of side 8 m in which temperatures down to -15°C could readily be produced and maintained to within 1 or 2°C over a period of an hour or more. Temperature measurements were made with a standardised thermometer situated at the level of the wind tunnel, and are considered to represent the conditions in the tunnel to within 1°C. Only temperatures of -12°C and above were used in order that the wet condition could be readily attained.

The air speeds employed were measured by placing a small anemometer in the tunnel. As the interior of the tunnel became rimed during the course of an experiment the velocity decreased slightly; the speeds given

are the mean of those measured at the beginning and end of each experiment and are considered to be correct to ± 5%.

Water droplets were sprayed into the room from a bank of eight sprays housed in an insulated box. Ordinary tap water was used and the sprays were directed towards the mouth of the tunnel from about 3 metres away, a distance sufficient for the droplets to cool practically to room temperature before being caught up in the airstream. The water concentrations were varied in steps according to the number of sprays in operation, and values up to 8 g m^{-3} could be produced at the velocities used.

Ice particles were introduced into the tunnel by sieving rime of low density (about 0.2 g cm^{-3}) through fine gauze near its mouth (see Fig.1), and the mixture of ice and supercooled water was blown over a set of three coaxial cylinders, rotated horizontally to give uniform deposits. The rate of rotation was one revolution every two seconds, so that the peripheral speeds of the cylinders were negligible in comparison with the airspeeds. The cylinders were constructed of thin brass sleeves mounted on heat-insulating formers, with outside diameters of 0.10, 0.63 and 1.43 cm.*. It was possible to remove a section of each cylinder so that the mass of the deposit per unit length could be determined for each diameter. The radial dimensions were obtained photographically or by assuming that the density of the deposit was 0.90 g cm^{-3}. The ice particles were dispensed manually at an approximately uniform rate, and the mass of ice used was determined by weighing the amount of ice in the

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* These cylinders were designed for experiments on the density and structure of accreted ice under dry growth conditions.

sieve before and after each experiment, the fraction actually entering the
tunnel being estimated visually.   When the surface of the deposit remained
just wet even though ice particles were also being accreted, it was possible
to obtain an independent measure of the ice concentration, since it could be
assumed that all the particles in the volume swept out by the cylinders were
being collected.   Ice concentrations up to 5 g m^{-3} were produced and
estimated to about $^+_-$ 30%.

The size distributions of the droplets and ice particles were obtained
by exposing in the tunnel narrow strips of perspex coated with oil and
afterwards photographing them through a microscope.   Each distribution was
obtained separately.   Two sets of sprays were used, giving drop volume
median diameters of 47 and 65 μ respectively.   The drop size is not
important for these experiments;   the two sets of sprays were used to
obtain smaller gradations in the liquid water concentration.   The number
distribution of ice particles was roughly constant from 20 to 300 μ and the
equivalent median volume diameter was estimated to be 260 μ .   It was not
possible to use larger ice particles as these could not be suspended in the
airstream long enough to reach the cylinders.

For given conditions of ambient temperature, airspeed and liquid water
concentration, droplets only were sprayed into the tunnel, and accretion
permitted to occur on a set of cylinders for a chosen time;   a period of
two to ten minutes was sufficient to build up a coating a few millimetres
thick at the liquid water concentrations used.   The experiment was then
repeated using another set of cylinders and adding ice particles to the
airstream.   Finally a third control experiment was performed using
droplets only.   The three sets of cylinders were photographed and

weighings made of sections from individual cylinders.   The agreement
between the mass measurements of the first and final experiments was
better than 10%.

3.   Results and discussion

3.1 Experiments using droplets alone

The critical liquid water concentration, W_c, which just maintains
the surface temperature of an accreting cylinder at 0^oC is given by the
following equation (Ludlam, 1952)

$$\frac{E \, W_c \, V \, (L_f + T)}{\pi} = \frac{0.24 \, (R_e)^{0.6}}{d} \, (L_v \, k \, \Delta \rho - KT) \qquad (1)$$

where L_f and L_v respectively are the latent heats of fusion and
vaporisation of water, T is the ambient temperature (in ^oC), E is
the efficiency of catch of the cylinder of diameter d, k is the
coefficient of diffusion of water vapour in air, V is the wind speed,
R_e is the Reynold's number, and $\Delta \rho$ is the water vapour density
difference between the riming surface and the environment.   The
expression on the LHS of the equation represents the rate of liberation
of heat at the surface and that on the RHS the rate at which heat is
removed by conduction and evaporation into the air flowing past the
cylinder.   The flow around the cylinders is assumed to be non-turbulent;
if the flow is turbulent then the transfer of heat may be increased by
perhaps 50% (McAdams 1954, p.261).   The validity of this equation has
been experimentally verified by Fraser, Rush and Baxter (1952) in icing
tunnel experiments.

The values of W_c have been computed from equation (1) for the present experimental conditions and these are plotted against the liquid water concentrations (corrected for values of the collection efficiency less than unity) deduced from the mass accreted on the cylinders (Fig.2). The four conditions of the ice surface indicated in the diagram are: "dry"; "just wet" as determined by a visible sheen on the surface; "wet" when the surface is covered by a liquid film; and "spongy". It can be seen that the liquid which may be retained by the cylinder exceeds the critical value deduced from Eqn. (1) by as much as 7 times.

Equation (1) defines the liquid water concentration in which the surface temperature of the ice deposit on the cylinder is just $0^\circ C$. If the water concentration is greater than the critical value then it is possible that an additional amount of water $(W_c - W)\,\dfrac{T}{80}$, be frozen if the temperature of the excess water is raised to $0^\circ C$ also. Further, when spongy, the deposit is readily moulded by the airstream, and becomes irregular and knobbly. This increases the surface area above that of a cylinder of comparable diameter, promotes turbulence and thus raises the rate of heat transfer.

The absorption of heat by the rotating cylinders should also be taken into account. The rate of heat conduction through the ice deposit into the cylinders may be comparable to the rate of transfer of heat to the environment so that the thermal capacities of the cylinders and of the insulating former cannot be ignored. These are such that, under the present conditions, the computed values of the critical liquid water concentration are likely to be low by as much as 20 to 50% in the case of the largest cylinder, depending on its initial temperature (normally

ambient temperature). In the case of the smallest cylinder, the heat absorbed is only a few per cent of that released by the freezing droplets, while the 0.63 cm diameter cylinder absorbs about one half as much as the largest one. The factor of 7 quoted above does not imply therefore that there was 7 times as much liquid as ice in the deposit; for this ratio a value of 2 or 3 is more likely, and was roughly confirmed by a visual examination when the deposits were broken up. Using a quantitative calorimetric method, List (1959) has determined values of up to 72% for the proportion of unfrozen liquid within similar spongy ice deposits.

Spongy ice was produced at all temperatures down to -12°C, the lowest employed in these experiments. There was, however, less tendency for significant spongy ice deposits to be produced at temperatures only just below freezing (-1 to -2°C).

3.2 Experiments with mixed clouds

If the accreting object has a wet or spongy surface layer, then it is obvious that an ice particle arriving with a speed of several metres per second can sink into it and be captured. This ice particle can remove the heat liberated by the freezing of a mass of water corresponding to the fraction $-T/160$ of its own mass (the specific heat of ice is about 0.5 cals g^{-1} $°C^{-1}$ and the latent heat of fusion of water about 80 cals g^{-1}) and become frozen into the surface. Consequently in mixed clouds the rate of freezing of collected liquid is increased.

The experimental data for the smallest cylinder in mixed clouds are shown in Table I; all the relevant quantities are converted to an effective spatial concentration (g m^{-3}). Since in most cases no

appreciable quantity of water was shed into the water of the cylinder, the water concentration given by the sprays is assumed to be that determined from the mass of the deposit. It was only at temperatures near $0^{\circ}C$ that these two quantities differed appreciably. The liquid water concentrations given by the sprays under these latter conditions was estimated from the rate of accretion at lower temperatures. The values given are considered to be correct to $\pm$ 20%.

If the surface was dry (i.e. $W < W_c$) then, although individual ice crystals were incorporated into the ice structure, no appreciable quantities of ice were accreted. For values of $W > W_c$, the maximum quantity of ice accreted depended on the excess water concentration $W - W_c$, as indicated in Fig.3: here it is seen that it was possible to use for accretion approximately 1 g m^{-3} of ice for each g m^{-3} of excess water. There is a dependence on the temperature, the amount of ice which can be accreted increasing with temperature rise. A better parameter to use is the quantity $\frac{W - W_c}{W_c}$ since this is a measure of the ratio of unfrozen to frozen liquid or the "degree of sponginess" of the deposit formed from the water droplets above. The relationship between W_1 and this parameter is shown in Fig.4. While there is still some scatter in the points, this does seem to be a better presentation of the data than Fig.3. The amount of ice which was accreted was approximately 1.4 times the value of $\frac{W - W_c}{W_c}$. In both these diagrams, for the reasons given above, W_c is an underestimate (by a factor of perhaps as much as 1.5 to 2 in the case of the largest cylinder) of the actual critical liquid water concentrations of the cylinders and this must be taken into account when applying these results to the growth of hailstones.

Plate I shows the iced cylinders after the experiments providing the data in the last entry of Table I.   The cylinders on the left were exposed to 7.5 g m^{-3} of droplets alone, the effective concentration was 0.8 g m^{-3}; the middle cylinders were exposed to 1.1 g m^{-3} of ice particles, and the right-hand side to 2.5 g m^{-3} of ice, in addition to the droplets.   The effective concentration in this last case was 7.8 g m^{-3}.   The additional liquid collected was far in excess of the amount which could possibly be frozen by heat transfer to the ice particles, which implies that the ice particles influence the manner in which the liquid water is held within the deposit.

3.3   The nature of the accretion process during wet growth

When all the liquid caught by an object in the supercooled cloud cannot be frozen, a film of water accumulates on the surface.   This film has been observed during the experiments and it was estimated that, at the airspeeds used (about 13 m/s), the thickness was a fraction of a millimetre, $\frac{1}{4}$ mm or less.   It was also noted that at the highest temperatures employed, the liquid water composing the film was blown rapidly to the downstream side of the cylinders, where droplets 1 to 2 mm in diameter were being shed into the wake.   The concentration of freezing nuclei (other than ice particles) which can cause nucleation at temperatures near 0°C is negligibly small, so that freezing progresses only outward from the surface of the solid ice deposit underneath the liquid film.   If the ice continues to grow as a compact mass of density about 0.9 g cm^{-3} as Ludlam (1958) suggests, there is

no way in which liquid water can be held within the ice structure and excess must be blown away.

When ice particles are also accreted, the circumstances can be greatly changed. Hallet (1960) considers that if an ice crystal alights with arbitrary orientation on a water surface which is barely supercooled, crystal growth occurs both along the surface and into the liquid, the structure in the latter direction being a system of branching dendrites. Provided there is effective nucleation, crystallisation at the surface of the liquid film is favoured, since it is cooler than the ice surface. When the number of accreted ice particles, and therefore of surface nucleation centres, is relatively large, an interwoven mesh of dendritic ice structures can be supposed to form within the film. This traps excess liquid water so that a mushy or spongy ice layer can develop and be retained if the mechanical strength of the dendritic system is sufficient.

An examination of the micro-crystalline structure of spongy ice deposits (see below) suggests that ice crystal concentrations of 1 to 10/litre are sufficient to ensure the trapping of liquid. Even if some of the droplets themselves did not freeze, incidental splintering from rimed auxiliary equipment could readily produce free ice particles in these concentrations. They are only fractions of a per cent of the droplet concentrations (order $100/cm^3$) and would be undetectable in the droplet stream. Nevertheless, their presence may be necessary for the formation of spongy ice deposits.

On the other hand, very little is known about the way in which ice crystallises from the liquid under the conditions of the wet growth regime. It is possible that the ice does not continue to grow outward as a compact

mass of high density, but that a crystalline structure similar to that envisaged in the last paragraph penetrates into the liquid film.

In Table I it can be seen that spongy growth was inhibited at temperatures only just below freezing, and it was not in fact until substantial quantities of ice particles were deliberately introduced into the airstream that considerable deposits were produced. In this case the spongy growth is presumably formed in a different way, the ice particles being frozen together irregularly into an open structure, the interstices of which filled with water.

In the case of wet growth on non-rotating objects, spongy projections can grow in much the same manner as icicles. As liquid flows to the back of the object it tends to stream off any irregularities; since the heat transfer is favoured at the surface, the irregularities continue to grow outward as partially frozen cylindrical projections. Such structures have been observed by the writer in the laboratory. Plate II shows a hailstone which, from its appearance, seems to have grown in this manner. Similar protuberances are found on many large hailstones.

There are therefore a number of possible ways in which the nature and structure of accreted ice may be affected during wet growth. Certainly water in excess of that which may be frozen is not always shed into the wake of the object, as formerly supposed; rather, at least a proportion can be incorporated into the ice structure and lead to growth rates much greater than previously envisaged. Ice particles, even when present in concentrations comparable with the droplet concentration, are readily incorporated into the deposit and, indeed, may be responsible for modifying the structure in such a way that none of the excess water is shed.

3.4 The micro-crystalline structure of ice deposits

Since ice is anisotropic, its micro-crystalline structure is readily observed by placing a thin slice between crossed polaroids. When viewed with white light, neighbouring crystals, being differently orientated, give rise to different colours, and are thereby easily distinguished.

Samples of spongy ice were formed on an ice rod placed in a stream of supercooled droplets. The airspeed, liquid water concentration and temperature in the droplet stream were about 10 m/s, 8 g m^{-3} and -12°C respectively. The spongy deposit was permitted to freeze completely and a section, about 0.3 mm thick, was made by melting it between two flat metal plates. Plate III(a) shows the appearance of this section when placed between crossed polaroids. The single crystals are 1 to 2 mm long so that their volume is the order of 10^{-3} cm^3. If it is assumed that each crystal is grown upon one freezing nucleus – an ice particle in this case, since the nucleation temperature is virtually 0°C – then the free-air concentration implied is 1 to 10/litre. The ice crystal concentration in the room was estimated visually to be 1/litre. After about 30 minutes the ice crystal concentration had increased to 100/litre, and a second experiment was performed under the same conditions with the result shown in Plate III(b). The dimension of the single crystals is smaller by a factor of about 4 to 5, implying an increase in the free-air ice crystal concentration of order 100, as observed.

This experiment shows that the internal structure of ice formed by accretion can be affected by the presence of ice crystals in the super-cooled cloud, and the observations of hailstone structure (see next section) may be interpreted on this basis.

3.5 The effect produced on the crystalline structure of the deposit by the freezing of droplets in the airstream

The supercooling of water has been investigated by a number of workers. Bigg (1953), for example, studied the supercooling of groups of water droplets of varying diameters (20 μ to 2 cm) suspended at the interface of two liquids of different densities. He showed that there was a linear relationship between the logarithm of the drop diameter and the median freezing temperature for each group. Langham and Mason (1958) have repeated these experiments using water of differing degrees of purity and they consider that Bigg's curves are typical of nucleation by foreign particles present in the liquid.

From a curve for rainwater given by Langham and Mason, the median freezing temperatures for groups of droplets of different sizes may be obtained, namely -8°C for droplets of diameter 1 cm, -19°C for a diameter of 1 mm, and -31°C for a diameter of 100 μ . The nuclei present in the water would cause freezing of the droplets in the airstream in corresponding concentrations (about 10^{-2}, 10 and 10^4 per litre respectively for a water concentration of 5 g m^{-3}) so that after they had nucleated the accreted water at these three temperatures, individual crystals about 1 cm, 1 mm and 100 μ across would be present in the deposit. For tap water the temperatures appropriate to these three sizes may be expected to be somewhat higher, for distilled water a few degrees lower.

It is apparent, therefore, that in normal icing experiments the crystalline structure of the deposits is dependent on the purity of the water used, as well as on other factors, and there is never complete certainty that the droplet stream is free of ice particles.

4. <u>Application to the growth of hailstones.</u>

The condition for the entry of hailstones into the wet growth regime may be expressed in terms of an equation similar to that for cylinders, there being a critical liquid water concentration for which the surface temperature is just $0^{\circ}C$. For spherical stones the critical concentration is given by (Ludlam, 1958)

$$E \pi R^2 V W_c (L_f + T) = 4 \pi Ra (L_v k \Delta \rho - KT) \tag{2}$$

where R is the radius of the stone and a the ventilation coefficient, the other symbols having the same meaning as before. The ventilation coefficient is a function of the Reynold's number (Re) and Ludlam takes it to be approximately $0.3 (Re)^{\frac{1}{2}}$. The condition for the entry of hailstones into the wet growth phase is illustrated in Fig.5. This gives the radius of the hailstone as a function of the ambient temperature under which the surface is just wet at various liquid water concentrations, in an environment whose other properties are about those encountered in hailstorm weather (Ludlam, 1958). If the position determined on the diagram by the temperature (or height) and size is to the left of the appropriate water concentration isopleth, the stone is in the dry growth regime; if the position is on the right-hand side, the surface of the stone is wet. In constructing this diagram, it has been assumed that hailstones fall with the speeds of spheres of density 0.90 g cm^{-3}. The high value for the density is justified by measurements made by Steyn (1950), Vittori and Caporiacco (1959) and Macklin, Strauch and Ludlam (1960). It has been found that the drag coefficient of actual stones of markedly aspherical shape may be almost double those of spheres of the same mass, but they fall in a preferred attitude in which the rate of accretion on the

collecting surface is considerably increased, so that even in these cases it is thought that the critical liquid water concentrations are unlikely to be underestimated by a factor of as much as 2. The curves show that even in modest liquid water concentrations, large hailstones are generally in the wet growth regime. However, if the ice deposited is spongy or if the cloud is partly composed of ice particles, this need not imply the considerable restriction on the growth rate formerly supposed, and in glaciated towers the concentration of accreted ice particles may well be such as to maintain the "dry" growth rate.

Examination of sections of hailstones a few centimetres in diameter indicates that the outer layers have been appreciably affected by the air flow (see, e.g., Ludlam and Macklin, 1959). The "front" surfaces are relatively smooth, while the "back" surfaces are very irregular, with knobs several millimetres across, and quite often a depression is observed in a roughly central position. Such shapes cannot be due to melting, since the change in size in falling to the ground is very small (Ludlam, 1958); it is considered that such a shape can arise only when the stone is very wet, and that the moulding by the airstream is enhanced when the ice is spongy.

As far as is known, large hailstones which arrive at the ground are hard; commonly they are reported to rebound from hard surfaces as much as several metres into the air. Thus, although a large part of the ice deposited during growth may be spongy, the outer layers of the large stones are probably frozen completely before their final fall, presumably

high in the cloud where the temperature is so low or the ice particle
concentration so high that there is a reversion to the dry growth regime.
The stones are then likely still to have liquid inclusions below the surface
layer.   It is not likely that this would be noticed at the ground, and
those stones preserved for examination have always been stored in a
refrigerator in which after a few hours they would become completely frozen.

When freezing spreads inwards in this manner from the outer surface,
the air which comes out of solution cannot escape but remains in bubbles
which are trapped in the ice and cause it to have a milky or opaque
appearance.   The radial cracks which are often observed in large hailstones
(see, e.g., Weickmann, 1953) may be due to the strains which arise as
freezing progresses under a hardened outer coat.

If hailstones grow by accreting significant concentrations of ice
particles as well as supercooled droplets, then this must be reflected in
their crystallographic structure.   The writer has examined, between crossed
polaroid, sections of some sixty stones which fell during a recent storm.
The sections were made in the way already mentioned, by melting down the
stones between parallel metal plates.   (This technique is useful only when
the densities of the stones are high and the melting process does not affect
the internal structure.)   In general the centres of the stones were
composed of a few single crystals, sometimes over a centimetre long, while
the outer parts were commonly composed of crystals a few hundred microns
across.   This was not always the case, however;   in some stones the central
crystals extended to the outer edge even though the stones were 3 to 5 cm
across.   (This investigation is being continued and the details will be
published later.)   The size of the stones examined was such that it is

probable that they were growing in the "wet" condition in the latter stages of their growth, so that the only nuclei which could have been effective are small ice particles.   It has already been shown that the size of the single crystals in spongy ice is affected by the presence of ice particles.   A possible interpretation of the micro-crystalline structure of hailstones is that it reflects the concentration of ice particles present in the cloud.

It must also be considered, however*, that if a hailstone is accreting only liquid water and has a surface temperature a little below $0^{o}C$, crystals may be produced by splintering processes during the freezing of individual droplets, of the kind described by Mason and Maybank (1960). These could also be incorporated into the hailstone structure and play a part in producing a micro-crystalline structure.

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* Private communications by Dr. B.J. Mason

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Table I

Experimental data for the smallest cylinder

T is the ambient temperature, v the velocity, W_c the critical liquid water concentration computed for the mean diameter of the iced cylinder, W the liquid water concentration, W_e the water concentration effectively caught by the cylinder when droplets were used, W_1 the concentration in addition to W_d caught when ice particles were used as well as the droplets, and m_1 the estimated concentration of the ice particles dispensed.

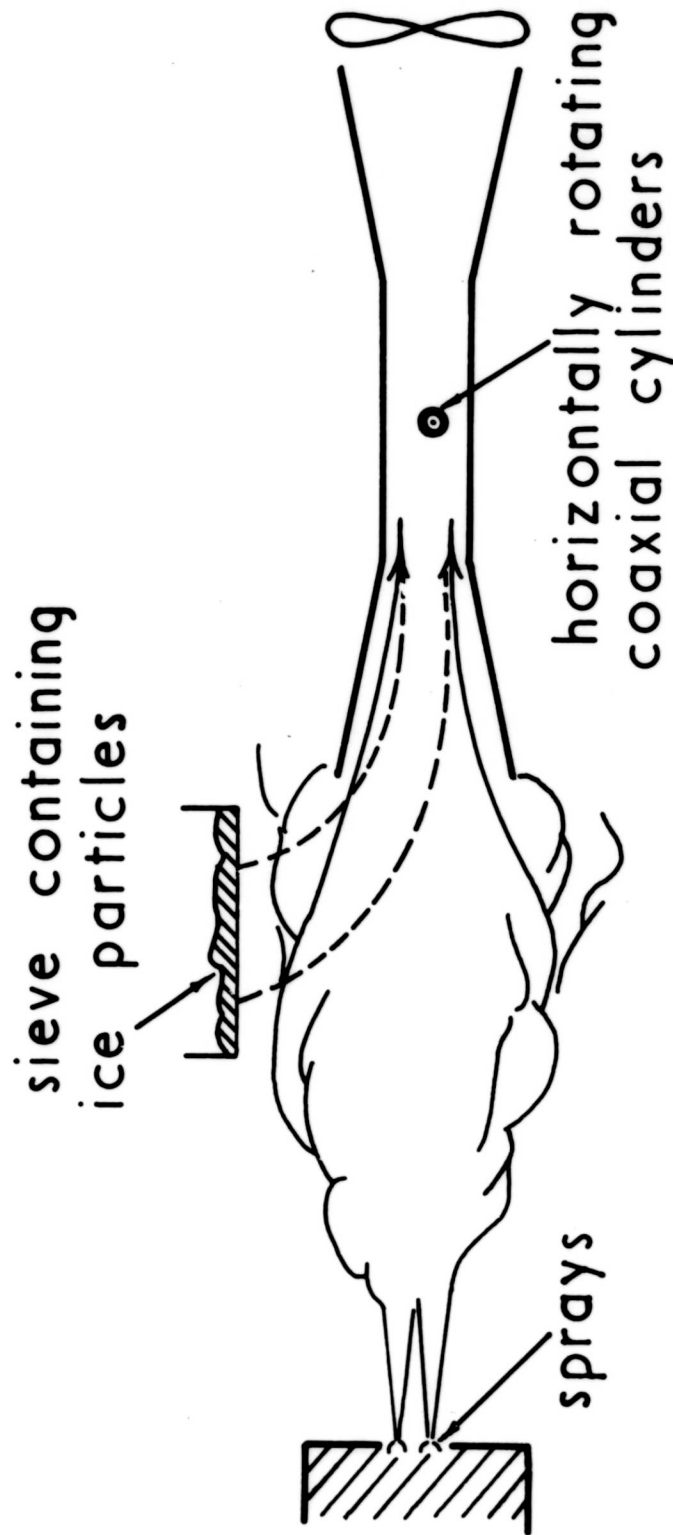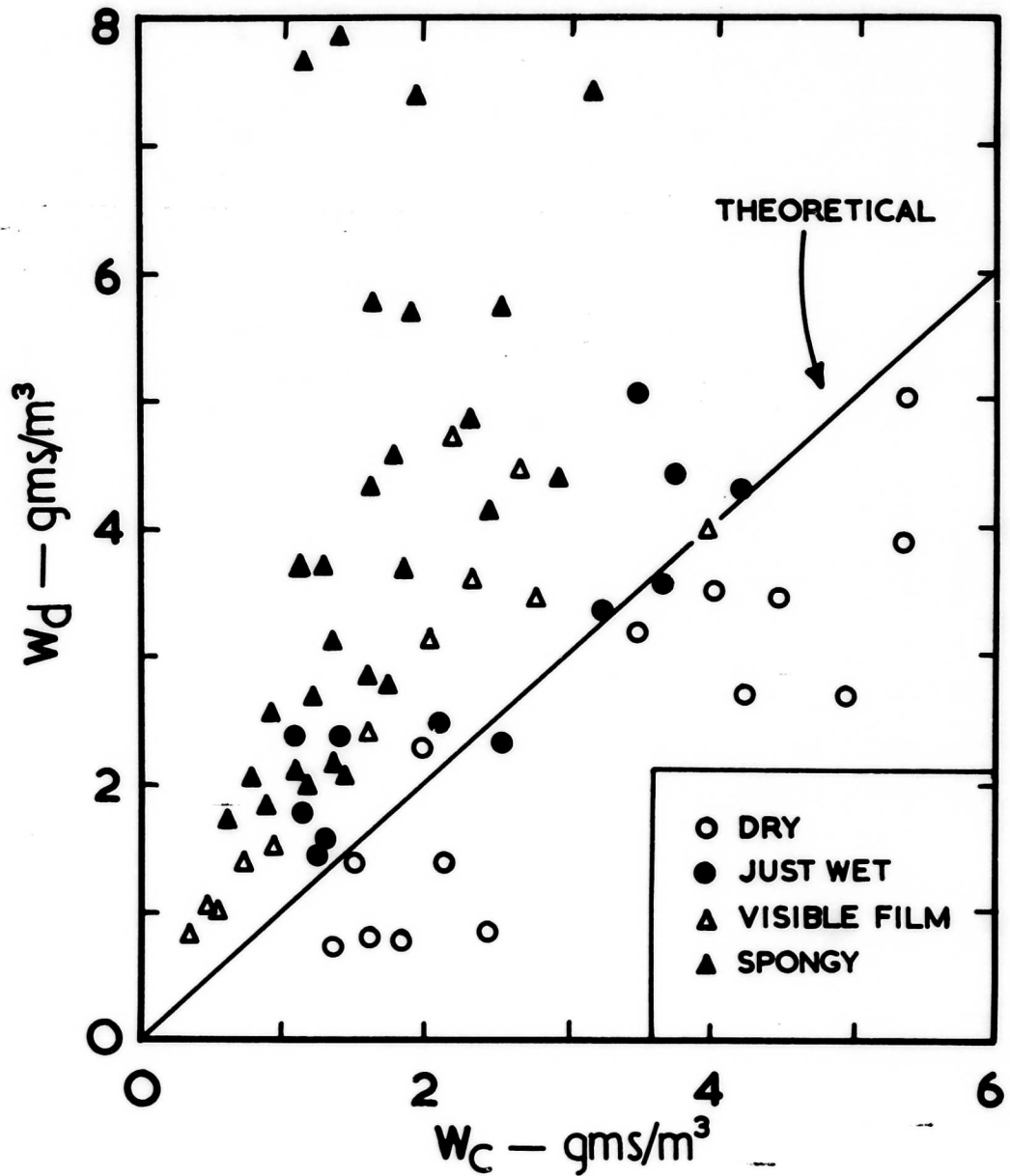| T	v	W_c	W	W_d	W_1	m_1
(°C)	m sec^{-1}	g m^{-3}	g m^{-3}	g m^{-3}	g m^{-3}	g m^{-3}
-12	13.2	4.0	4.0	4.0	0	2.1
	13.5	3.7	3.6	3.6	0	1.9
- 8	13.6	2.6	2.4	2.4	0	2.2
- 7.5	12.8	2.5	0.9	0.9	0	1.9
			5.8	5.8	1.4	1.4
					1.6	2.0
- 7	12.6	2.5	4.2	4.2	0.9	1.5
					0.6	5.3
	12.8	2.2	1.4	1.4	0	2.7
- 6	12.8	1.9	3.7	3.7	2.6	3.0
	13.0	1.9	7.5	7.5	2.6	2.8
					3.3	5.7
- 5	12.8	1.7	2.8	2.8	1.1	2.9
- 4.5	12.6	1.4	2.2	2.2	1.3	3.2
- 4	13.1	1.4	2.1	2.1	1.0	2.7
- 2	13.3	0.9	2.0	1.4	1.1	1.1
					2.3	2.9
- 1.5	13.3	0.8	7.5	1.4	3.6	1.1
					7.3	2.5

FIG. 1. Schematic diagram of experimental arrangement.

FIG. 2. The liquid water concentration effectively caught by the cylinders, W_d g m^{-3}, plotted against the critical liquid water concentration, W_c g m^{-3}.
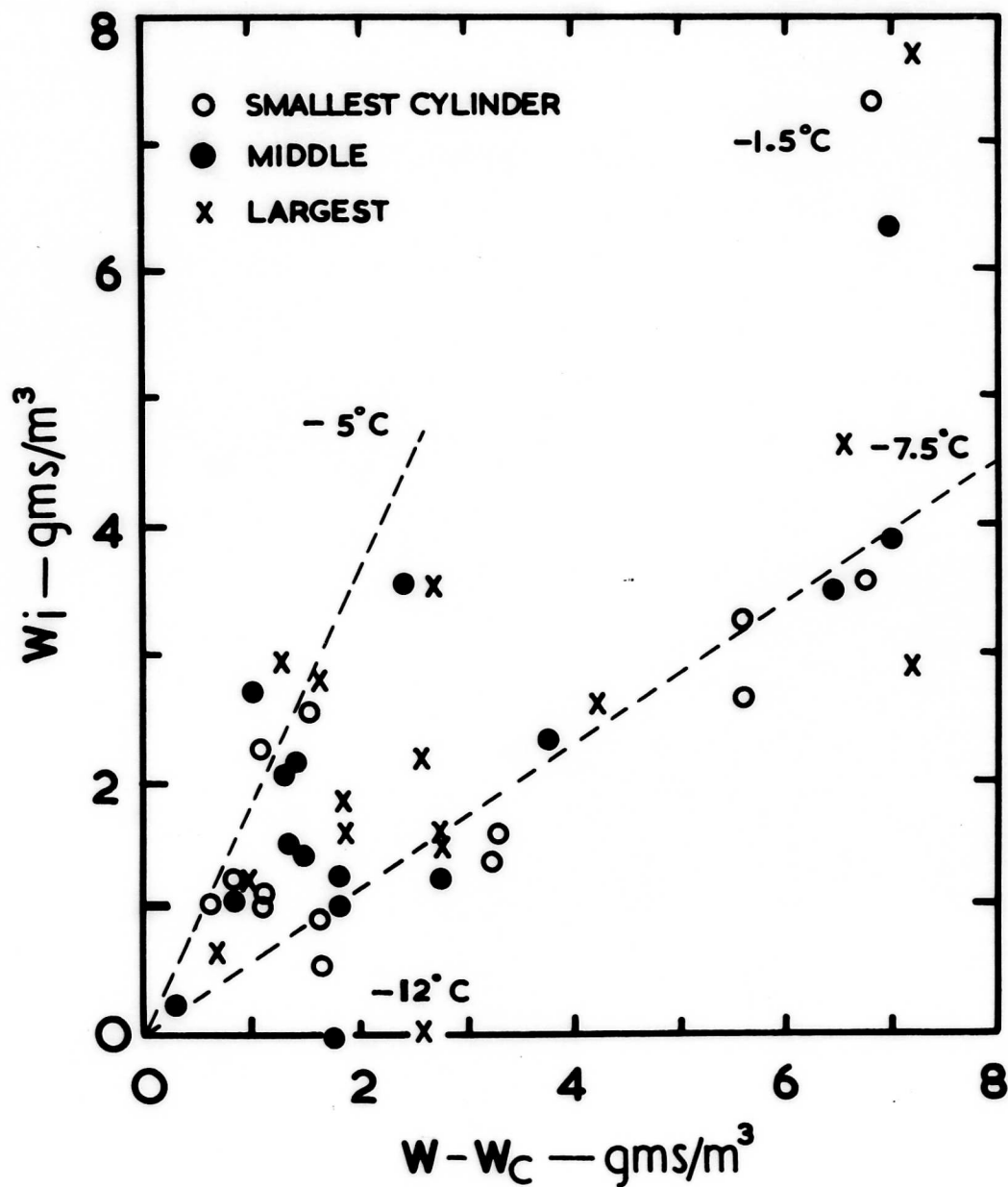
FIG. 3. The concentration of ice particles, W_i g m^{-3}, accreted in addition to the supercooled droplets, as a function of the excess liquid water concentration, $W - W_c$ g m^{-3}.
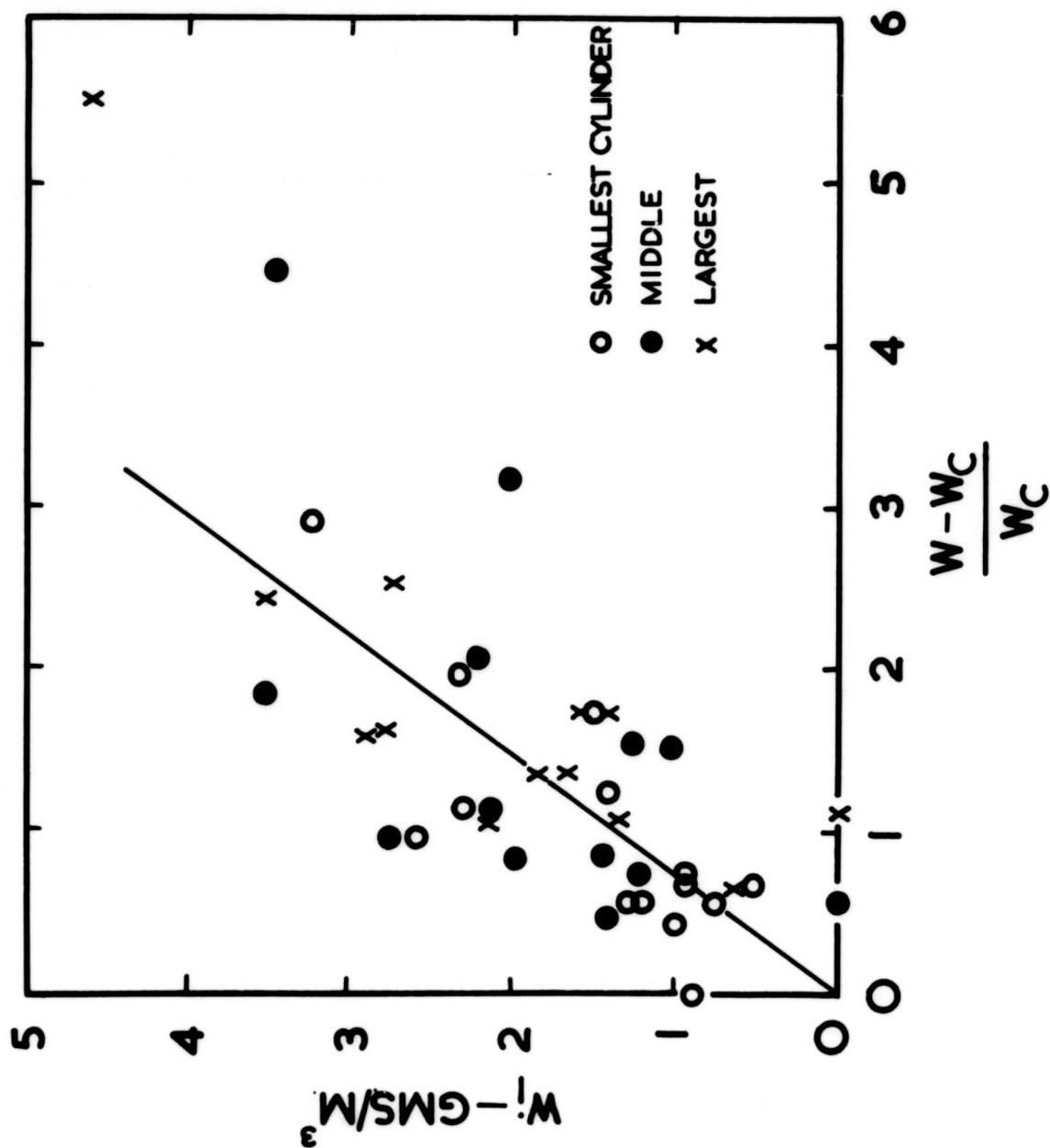
FIG. 4.   The concentration of ice particles, W_i g m^{-3}, accreted in addition to the supercooled droplets, as a function of the quantity $\frac{W - W_C}{W_C}$.
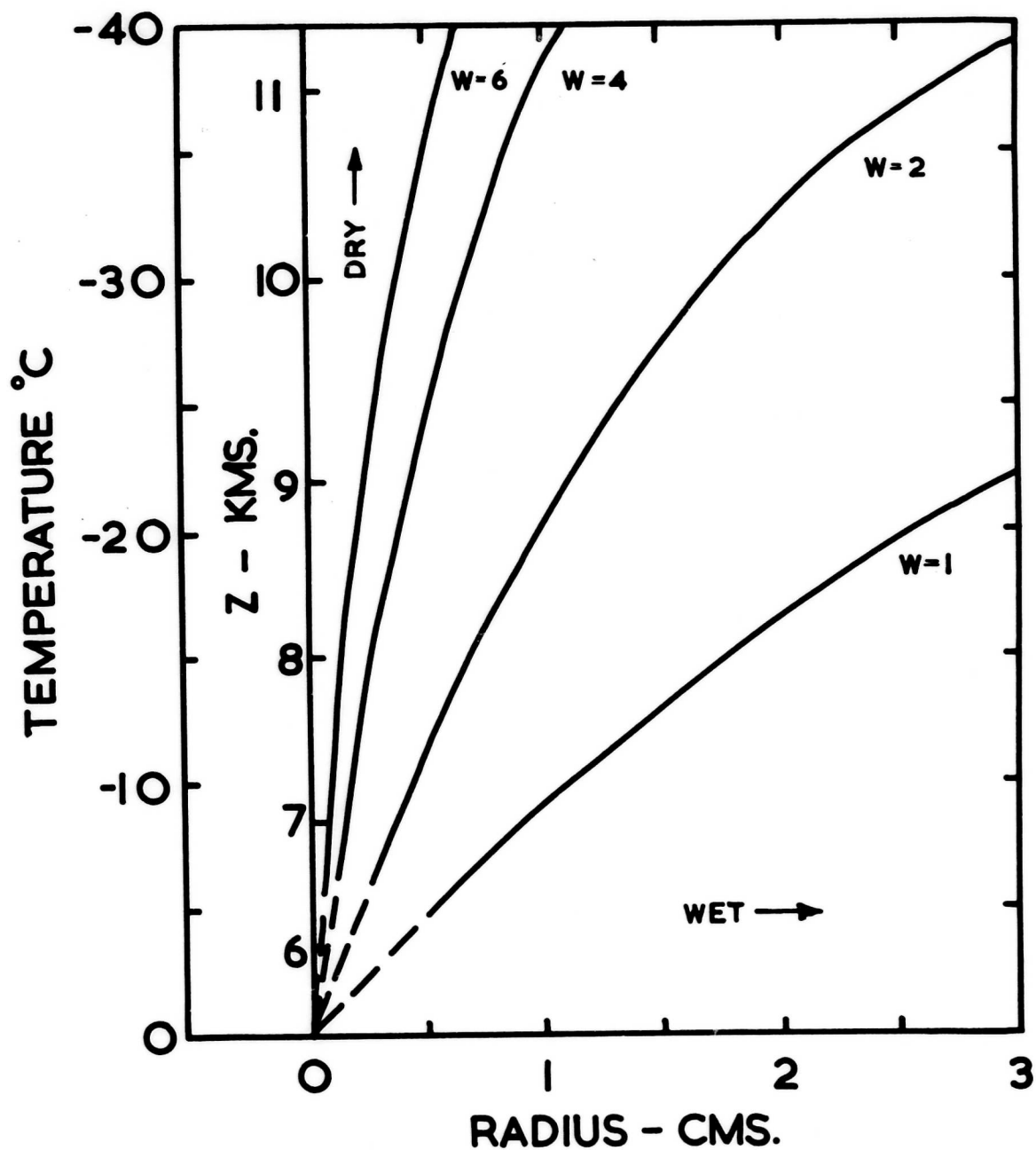
FIG. 5. The condition for the entry of hailstones into the wet growth phase. If the position of a hailstone on the diagram (determined by its size and the cloud temperature) is to the right of the appropriate liquid water concentration isopleth, then its surface is wet; if to the left its surface is dry.
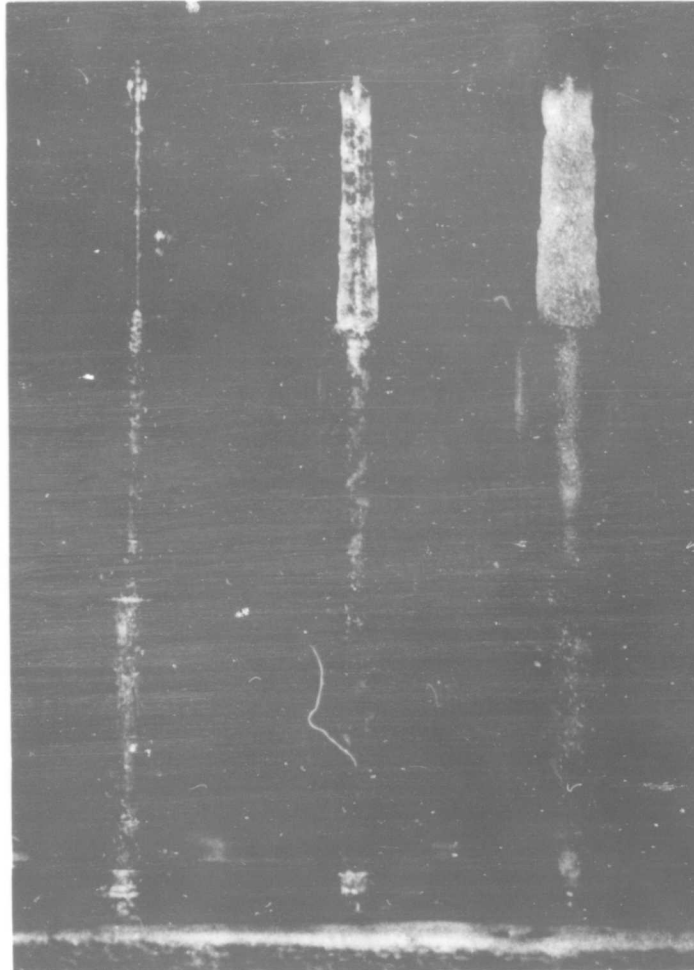
PLATE I.   The iced cylinders after the experiments pro-
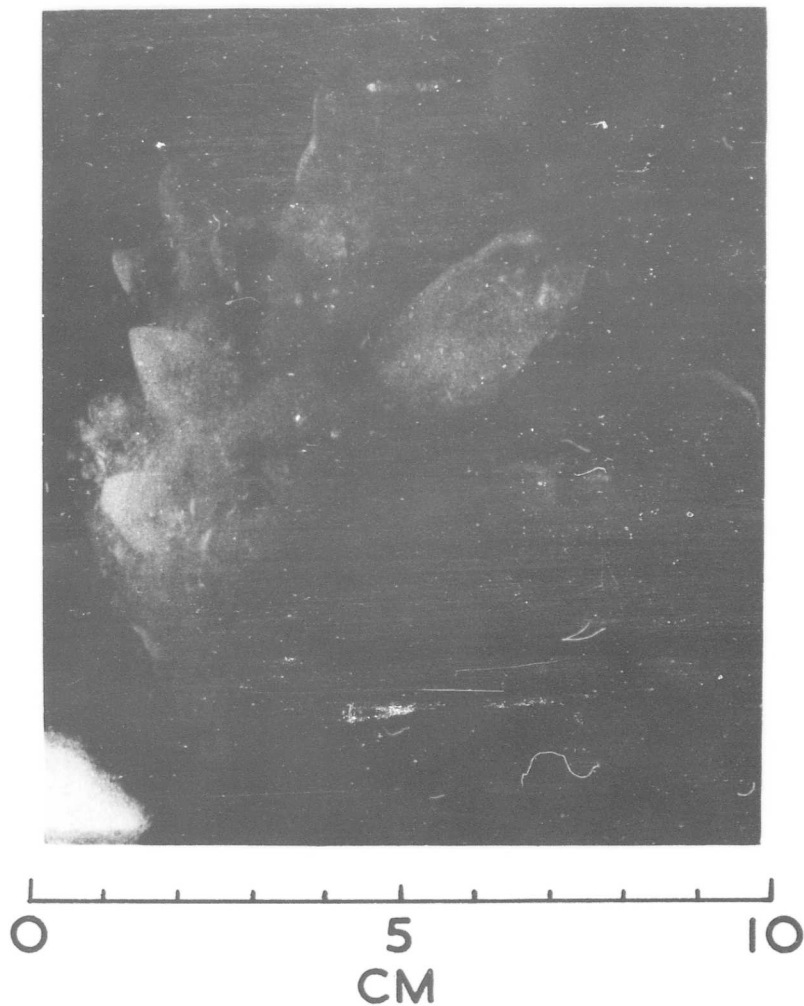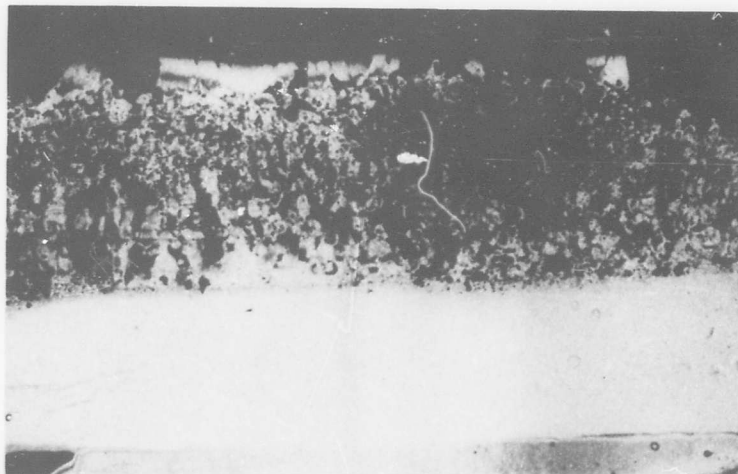viding the data in the last entry of Table I.

PLATE II. Hailstone which fell at Pretoria, South Africa,
November 1949. Photo by courtesy of the South
African National Bureau of Standards.

a

b

PLATE III.   Thin sections of spongy ice viewed
             between crossed polaroids.